Dark Tridents @ Off-Axis Liquid Argon Neutrino Detectors

Yue Zhang

Fermilab & Northwestern

Workshop on Physics Opportunities in the Near DUNE Detector Hall, Dec 5, 2018

André de Gouvêa, Paddy Fox, Roni Harnik, Kevin Kelly, **YZ**

(arXiv:1809.06388)

DUNE is a Multi-purpose Experiment

DUNE will be one of the largest particle physics experiments in the coming decade. New generation of ν detectors.

Besides its day job: In the history, there has been a fascinating tradition for ν detectors to discover unexpected signals.

Suggestion of this talk: let us try to get prepared for the unexpected. New dark matter signals from light weakly coupled dark sector theories.

Dark Matter at Neutrino Detectors

For non-relativistic halo dark matter, available recoil energy in the elastic scattering

$$E = \mu v^2 = 10^{-6}\mu \lesssim \text{a few hundred keV} < E^{\text{th}}_{\nu-\text{detector}}$$

Energy threshold of neutrino detectors: $E^{\text{th}}_{\nu-\text{detector}} \sim$ MeV.

A inspiring challenge. Design new low threshold detectors, or

Consider new dark matter theories that offer larger E.

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A inspiring challenge. Design new low threshold detectors, or Consider new dark matter theories that offer larger E.

Borexino as exception: $E^{\rm th}_{\rm Borexino} \sim 200$ keV, sensitive to DM velocities close to cutoff (halo), stronger annual modulation effects.

Eby, Fox, Harnik, Kribs (private communication)

Make Dark Matter More Energetic

- Neutrino beam: ν-philic dark matter carries away MET. [ND]

Jeffrey Berryman's talk

de Gouvêa, Berryman, Kelly, **YZ** (1802.00009), Kelly, **YZ** (to appear)

- Create a dark matter beam striking on ν-detector. [ND]

Batell, Pospelov, Ritz (0906.5614)

- Boosting dark matter due to astrophysical origins. [FD]

Berger, Shin's talks

Bringmann, Pospelov (1810.10543)

- Self-Destructing Dark Matter. [FD]

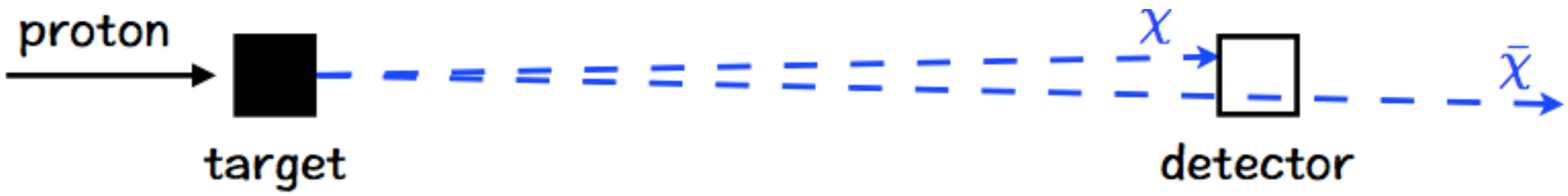
Grossman, Harnik, Telem, **YZ** (1712.00455)

[N(F)D=near (far) detector]

This Talk

- Create a dark matter beam striking on ν-detector. [ND]

This Talk



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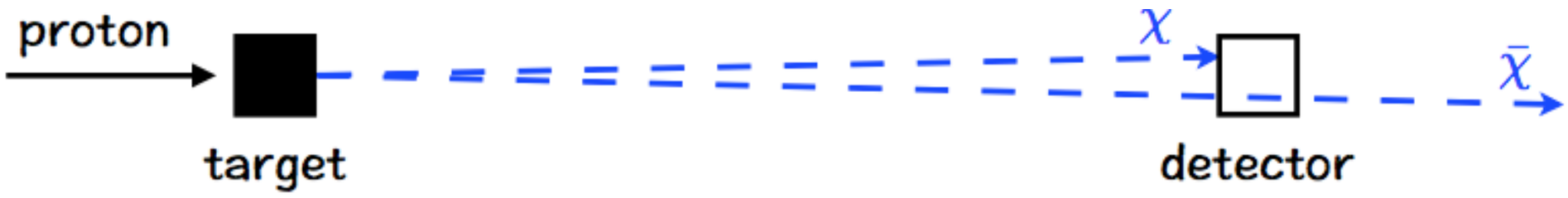


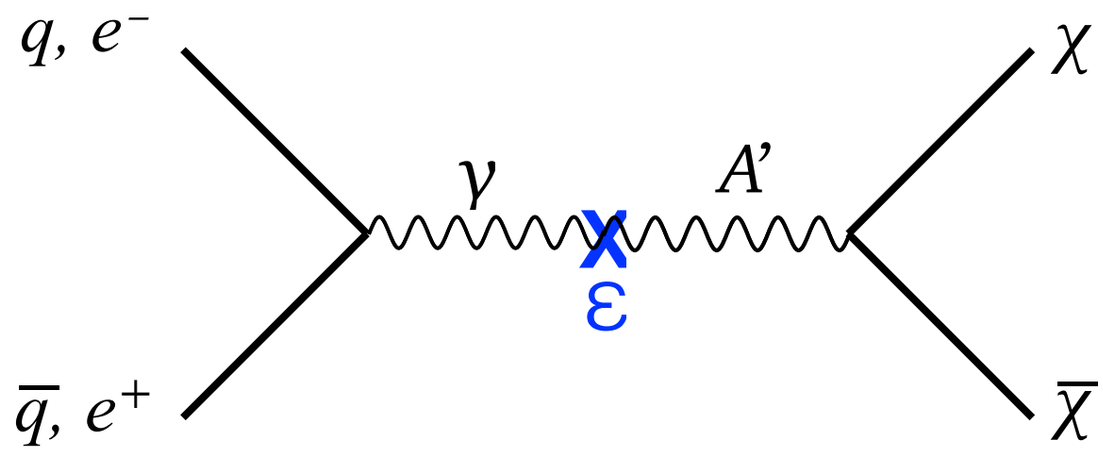
- Create a dark matter beam striking on ν-detector. [ND]

- I will present our new idea, and explain why it is important, based on existing LAr detectors, e.g. MicroBooNE.

- Many similar aspects apply to the DUNE near detector.

Benchmark Model

The dark analog of QED: massive dark photon A' portal to DM χ (fermion or scalar).

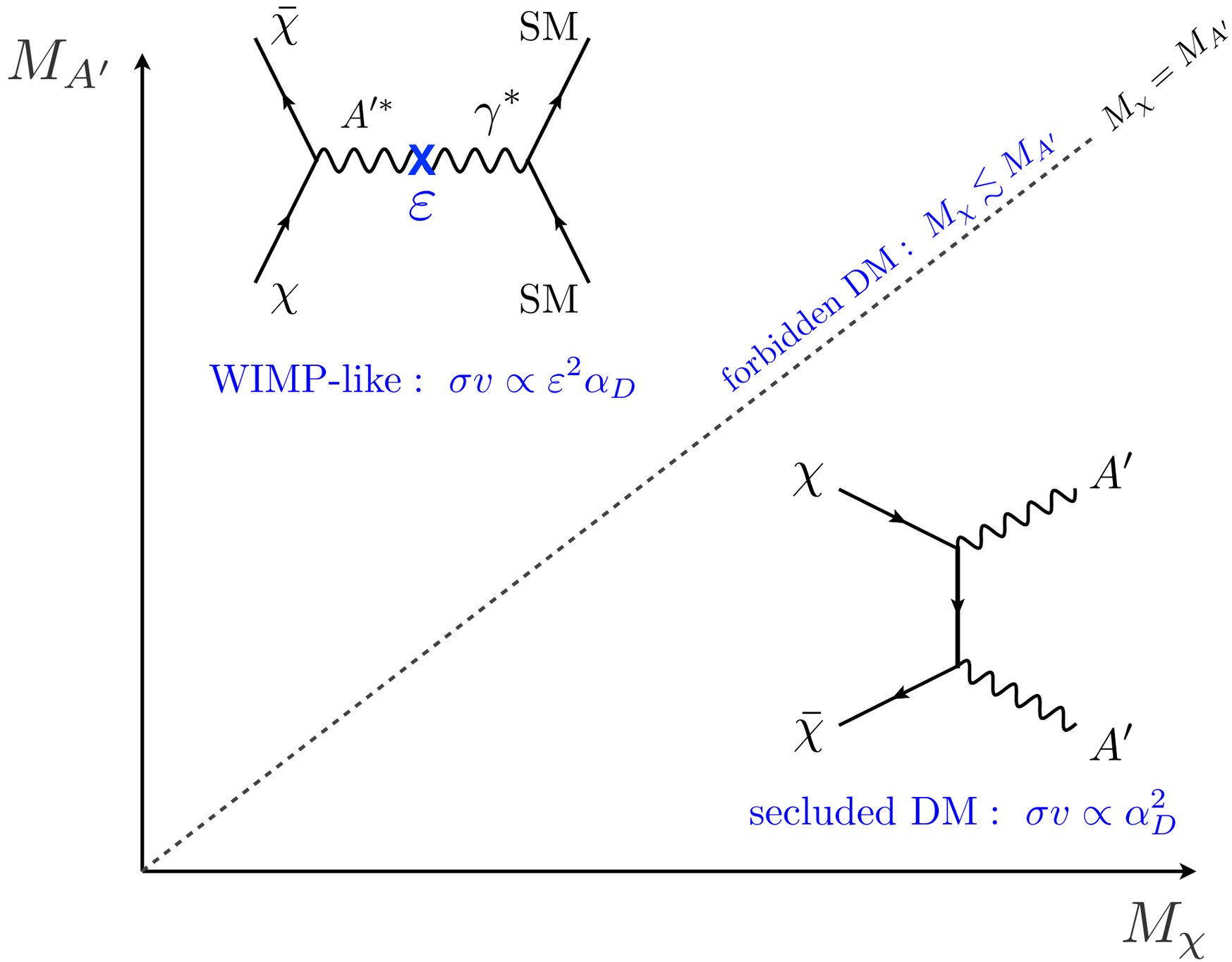


$$\mathcal{L}_{\rm int} = \left(\varepsilon e J^{\mu}_{\rm SM} + g_D \bar{\chi}\gamma^{\mu}\chi\right) A'_{\mu}$$

strong limits from dark photon searches

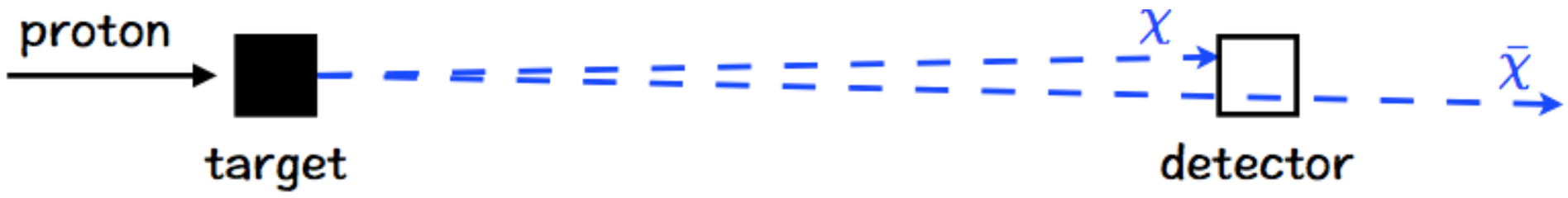
allowed to be sizable

Roadmap From Early Universe



Dark Matter Elastic Scattering

Light dark particles can be probed at neutrino experiments.



$\pi^+ \to \mu^+ \nu_\mu$

$\pi^0, \eta, \cdots \to \gamma A', \; A' \to \chi\bar{\chi}$

$\nu_\mu n \to \mu^- p, \; \nu_\mu n$

$\chi p \to \chi p \;\; (t\text{-channel } A')$

Same signal as neutrino neutral-current interaction (background here).

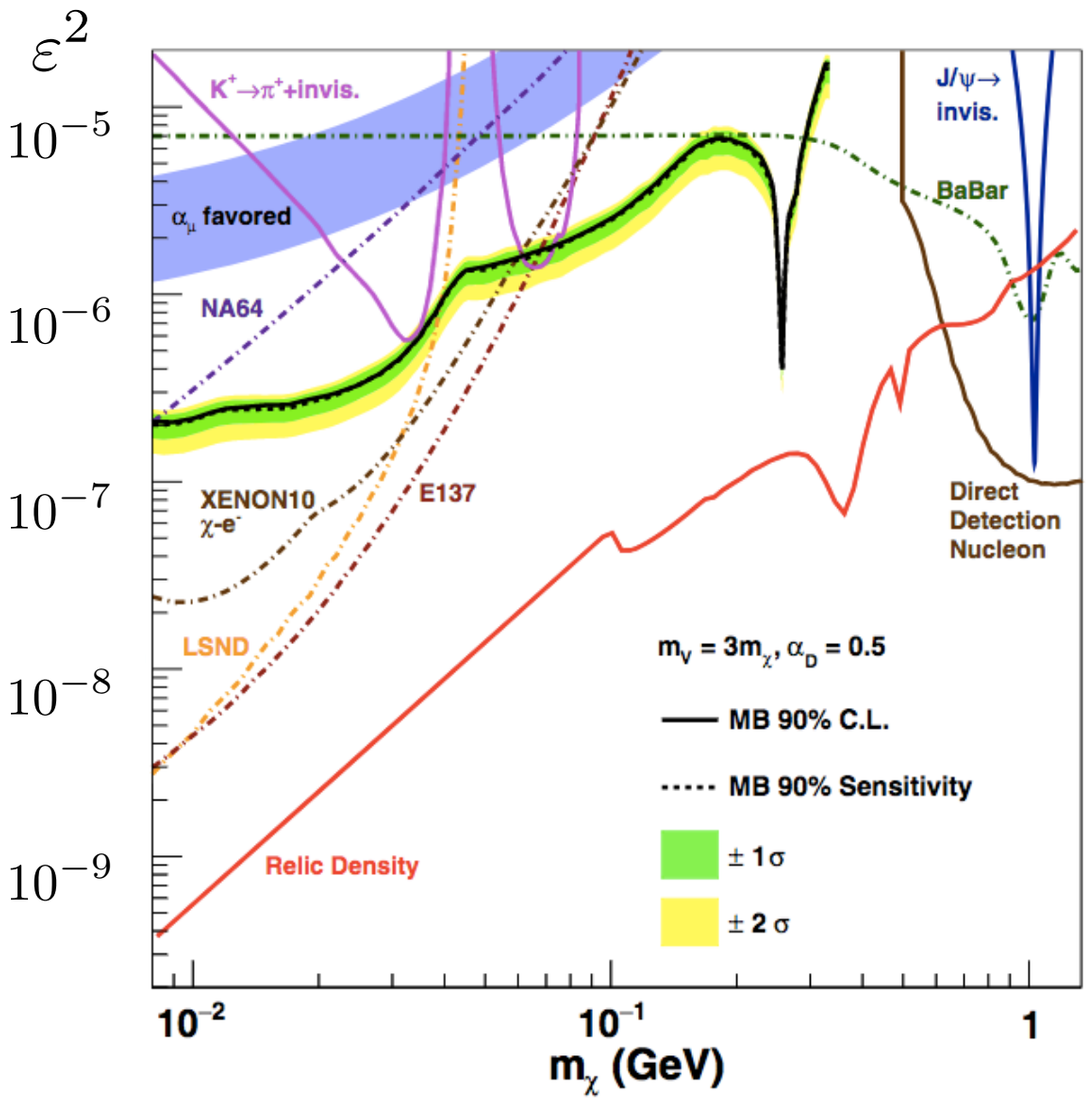
Flux ratio: $\dfrac{\Phi_\chi}{\Phi_\nu} \sim \varepsilon^2$

Scattering cross section ratio: $\dfrac{\sigma_{\chi p}}{\sigma_{\nu p}} \sim \dfrac{\varepsilon^2 e^2 g_D^2 / M_{A'}^4}{g^4 / M_W^4}$

χ scattering important if $\varepsilon \gtrsim \dfrac{M_{A'}}{\sqrt{g_D} M_W} \sim 10^{-3} \left(\dfrac{1}{g_D}\right)^{1/2} \left(\dfrac{M_{A'}}{100\,\mathrm{MeV}}\right)$

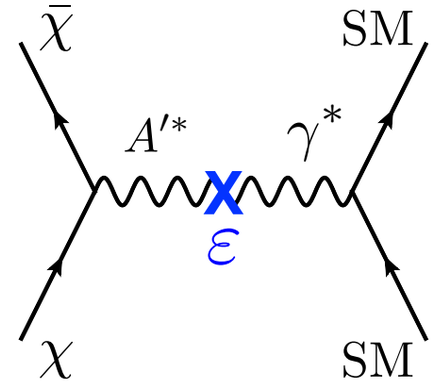
Batell, Pospelov, Ritz (0906.5614)

Limits From MiniBooNE



$\alpha_D = 0.5$

$M_{A'} = 3M_\chi > 2M_\chi$



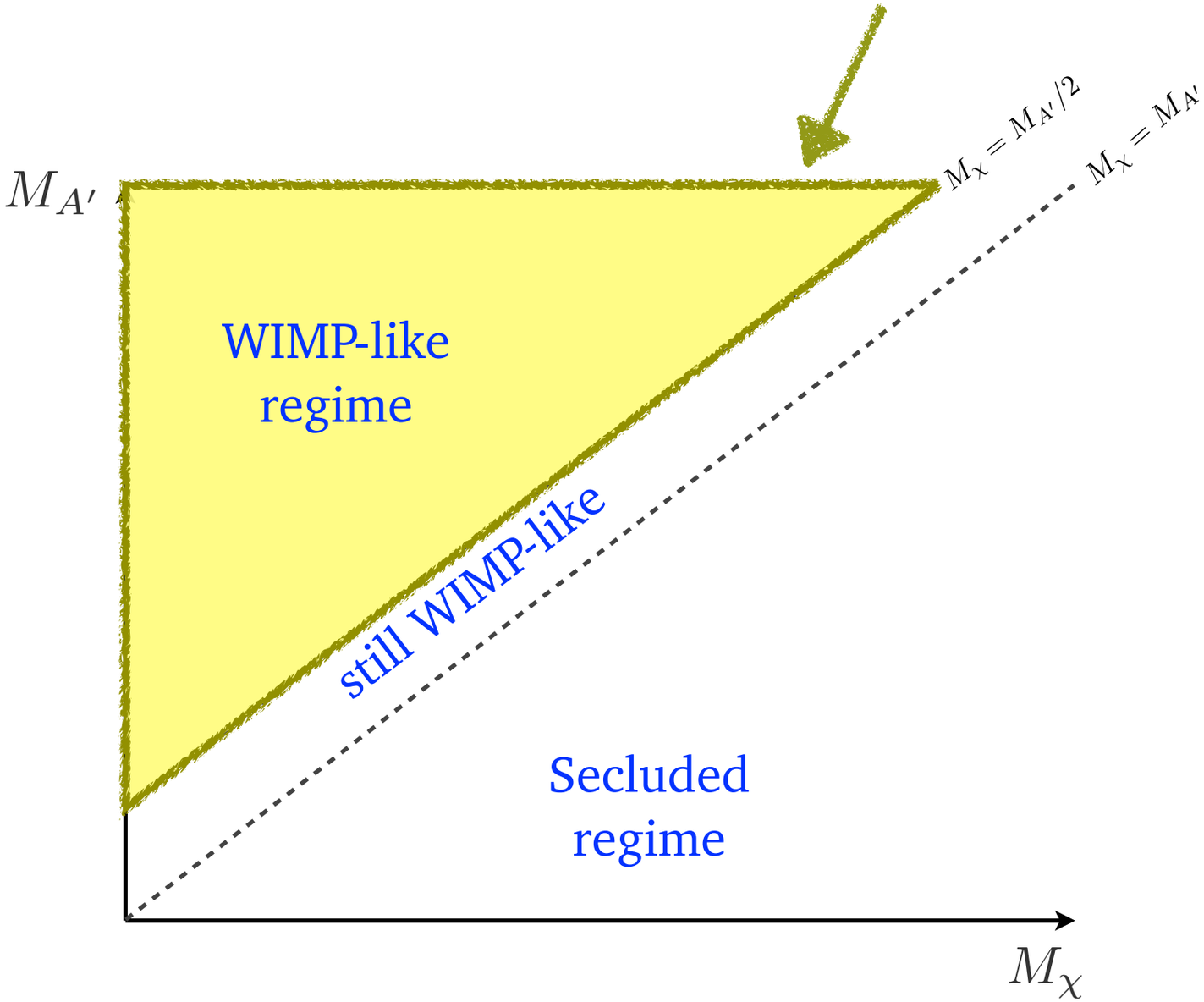
thermal freeze out channel

Beam dump mode run in 2012-13. Look for nuclear (electron) recoils.

MiniBooNE-DM Collaboration (1702.02688 & 1807.06137)

Complimentary Regions on the Roadmap

Almost all studies of elastic beam DM scattering have focused on the parameter space with $m_{A'} > 2m_\chi$ — on shell intermediate A'.



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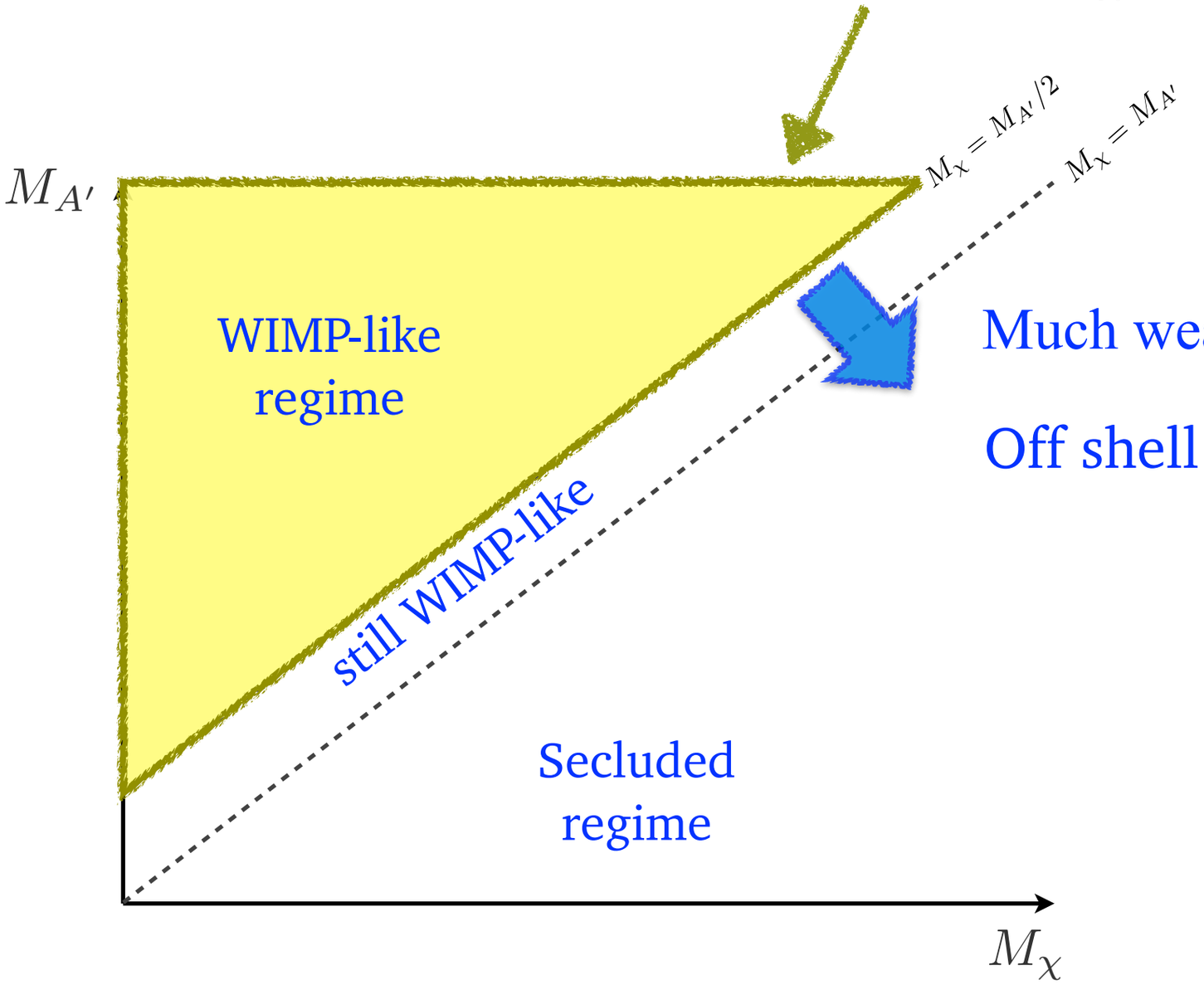
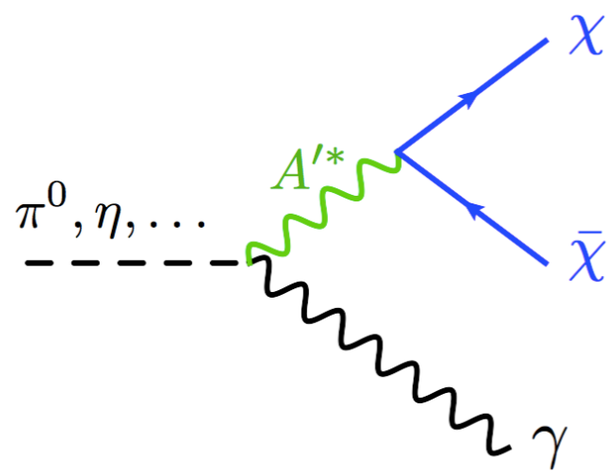


Much weaker limits for $m_{A'} < 2m_\chi$

Off shell A' for DM production



New Dark Matter Signals

Elastic scattering limited by large ν background (SM NC interactions). New ways of probing the $m_{A'} < 2m_{\chi}$ regime?

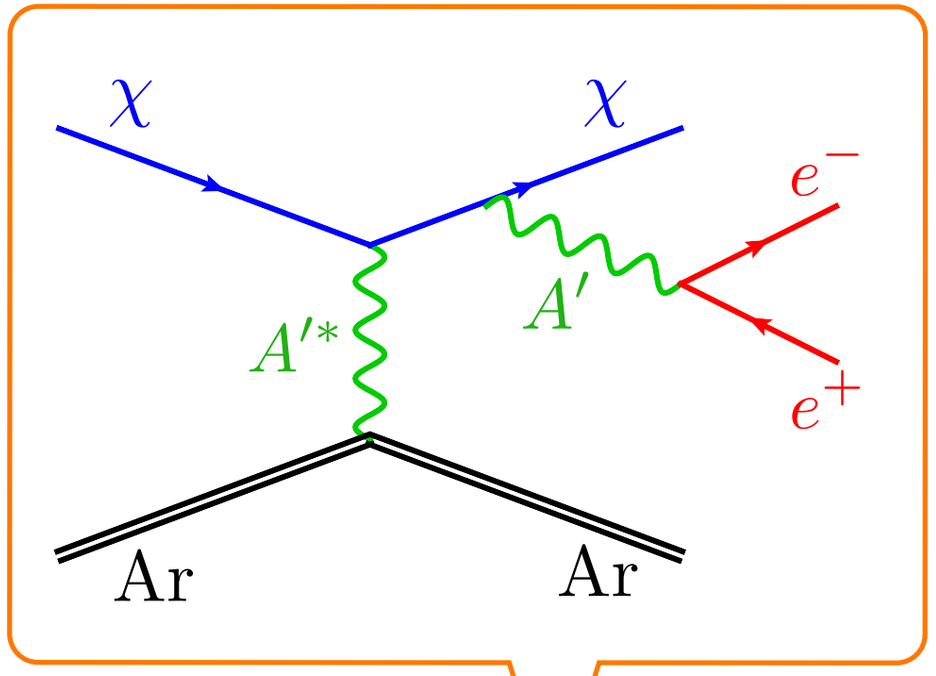
Consider more rare processes (in view of neutrinos) that are triggered by dark matter.

Dark Tridents

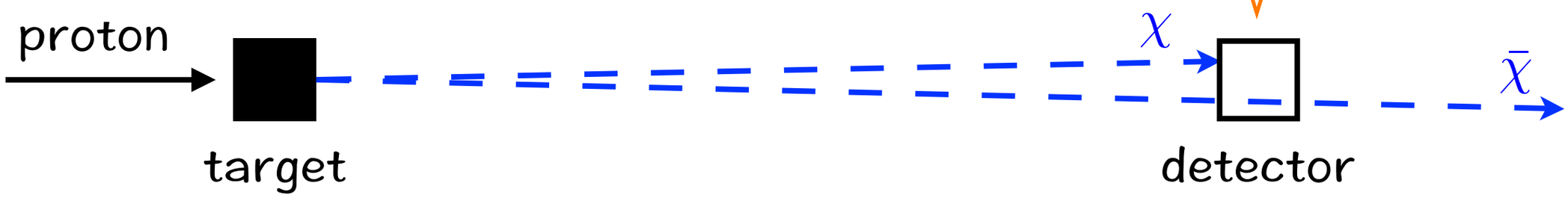
Go beyond elastic scattering: consider *A*' radiations. *A*' (on-shell) has to decay back into SM. Take advantage of its visible decay.

Signal: charged-lepton pair creation.

$$\frac{\sigma_{\chi N\to\chi N+A'}}{\sigma_{\chi N\to\chi N}} \sim \frac{\alpha_D}{2\pi}\log\frac{Q^2}{M_{A'}^2}$$



Dark showers possible in the large α_D and large *log* limit.



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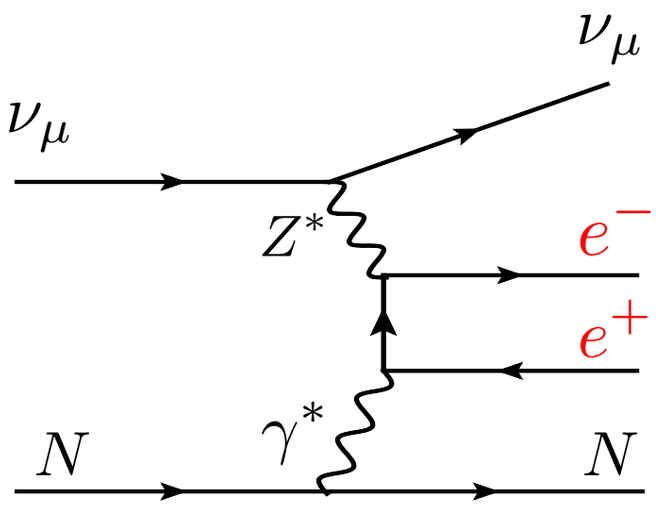
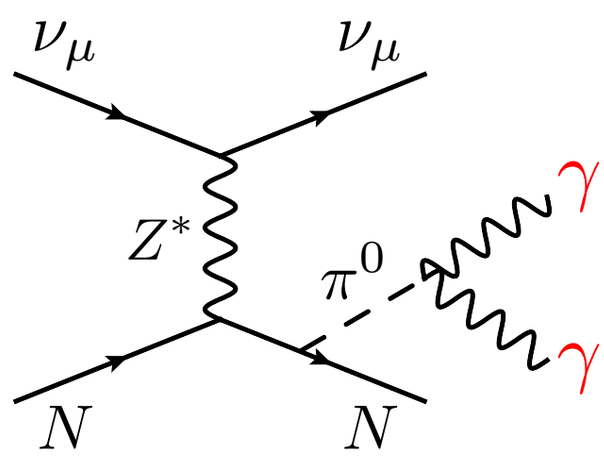
Background

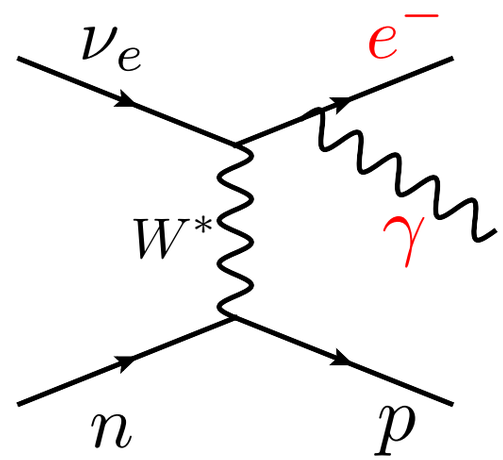
Neutrino trident production



$\sigma_{\nu\text{-trident}} \sim 10^{-5}\sigma_{\text{NC}}$

Fake signals





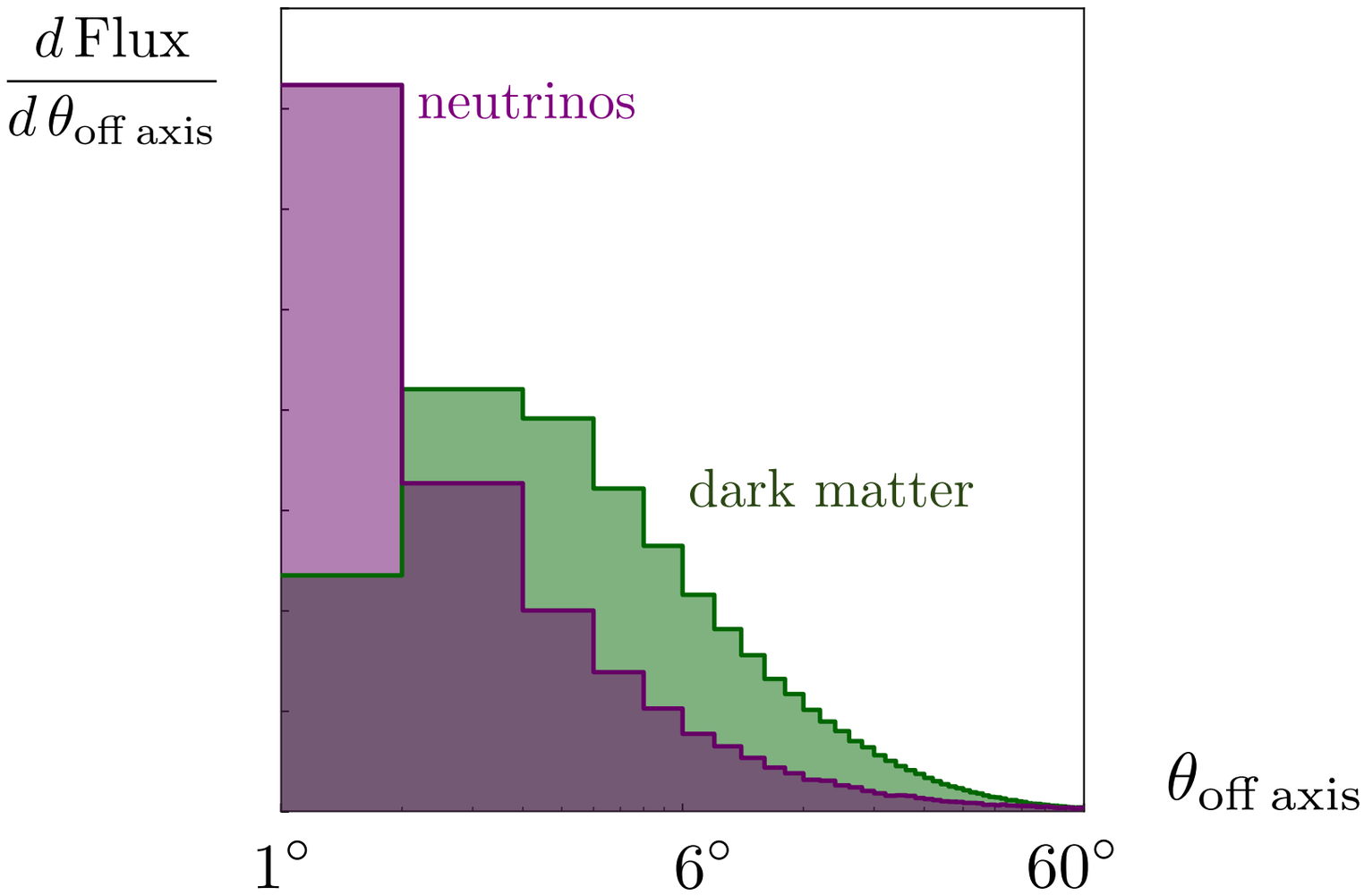
Require good particle ID (LArTPC)

Perez-Gonzalez, Hostert's talks

Invariant mass cut: $m_{e+e-} = m_{A'}$ for all dark trident signal events.

Dark Matter Beam is Wider

Without a dedicated running in the beam dump mode, Off-axis detector sees a relatively higher dark matter/neutrino ratio.



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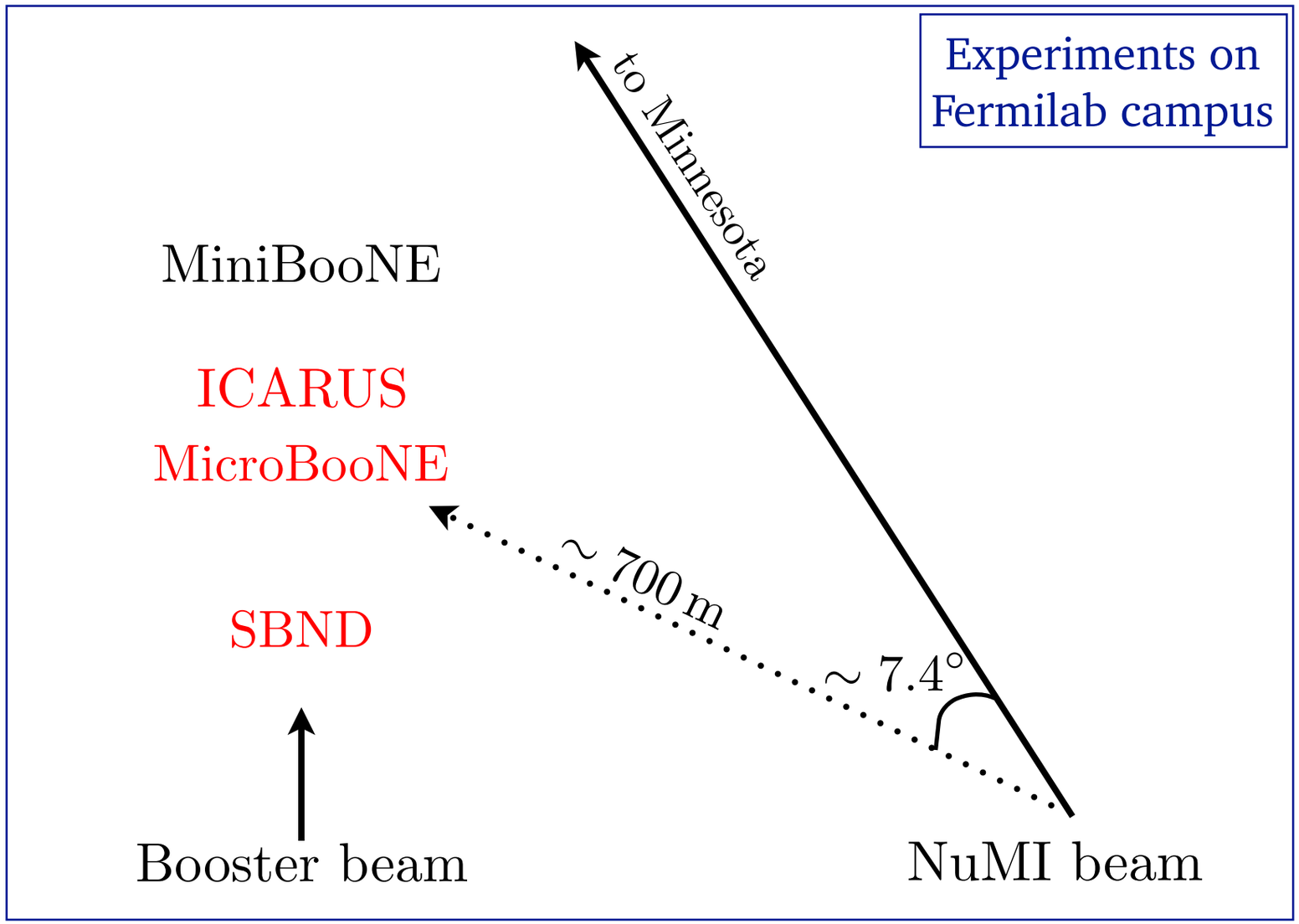
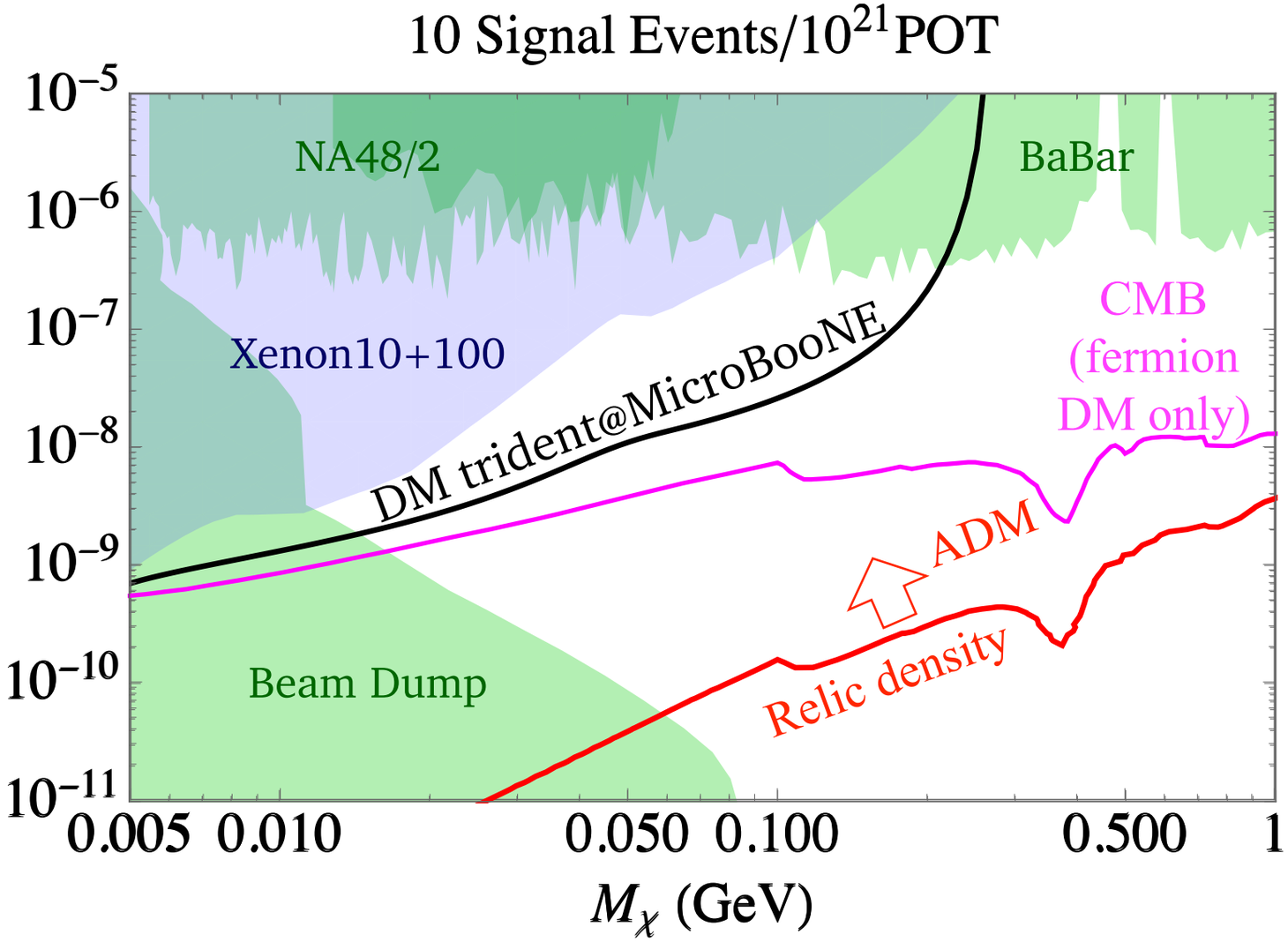
We Already Have Data On Tape



Since MicroBooNE began taking data in 2015, NuMI has delivered ~10^{21} POT. ν-related background events estimated to be ~ $O(10)$.

(without $m_{e^+e^-}$ cut)

Dark Trident at MicroBooNE: Reaches



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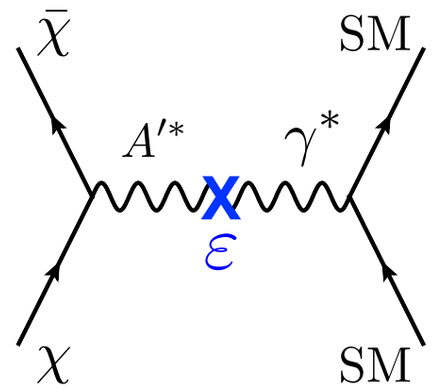

freeze out channel

Better sensitivity using dark trident than elastic scattering.

CMB constraint does not apply to complex scalar, or ADM.

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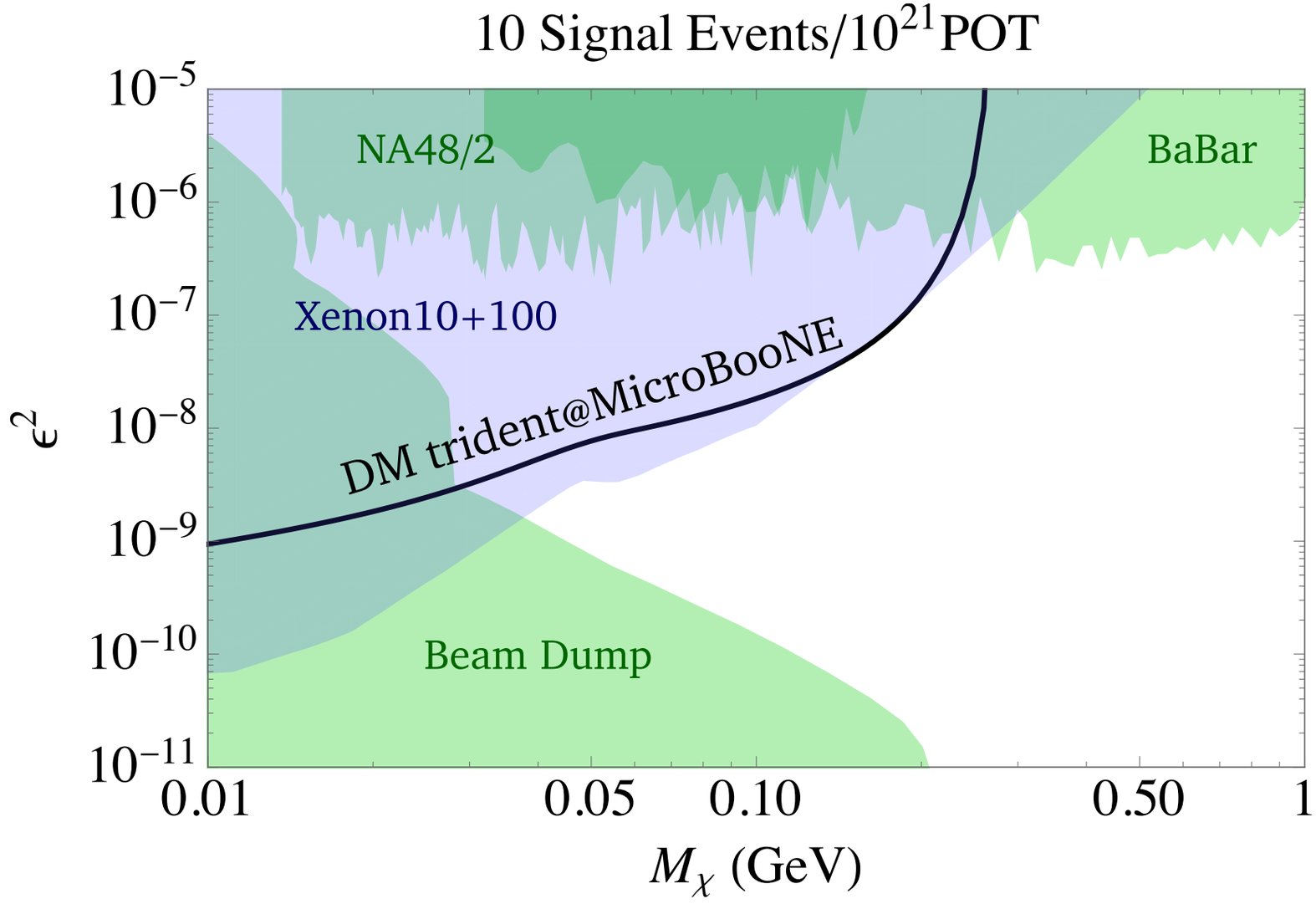
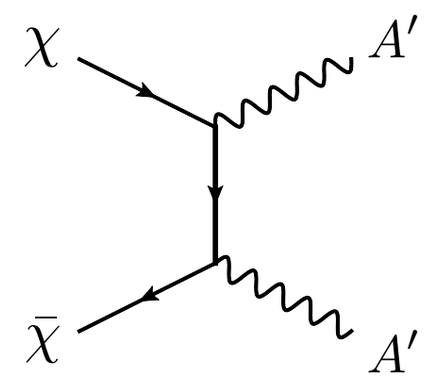


Secluded scenario:

$\alpha_D = 0.5$

$M_{A'} = M_\chi/2$



freeze out channel

A positive discovery of ε away from the thermal targets could help differentiate DM production mechanisms.

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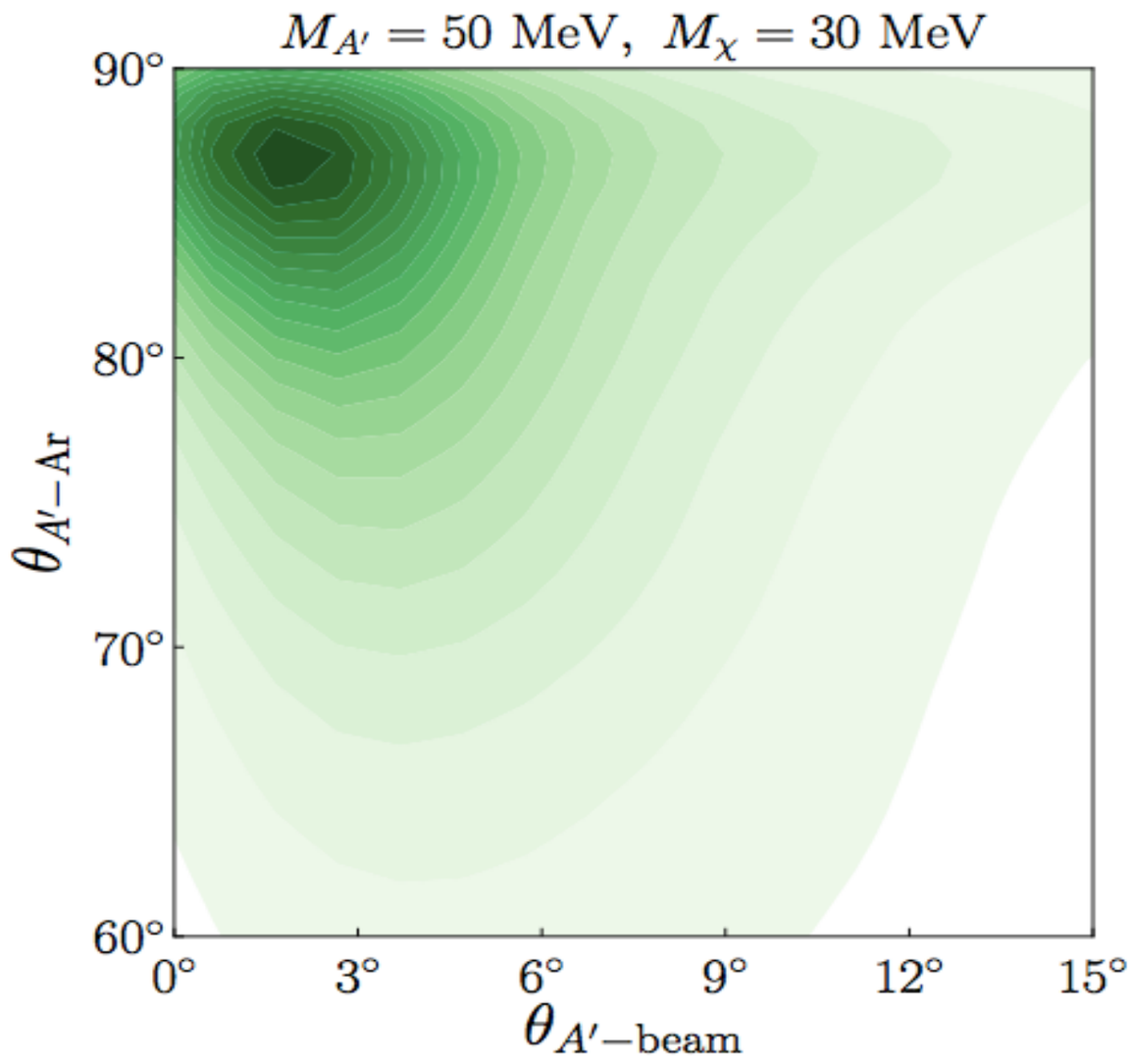
A Closer Look: angular distributions



Interestingly, outgoing *A'* most likely to travel along beam direction, with nuclear recoil perpendicular to beam direction.

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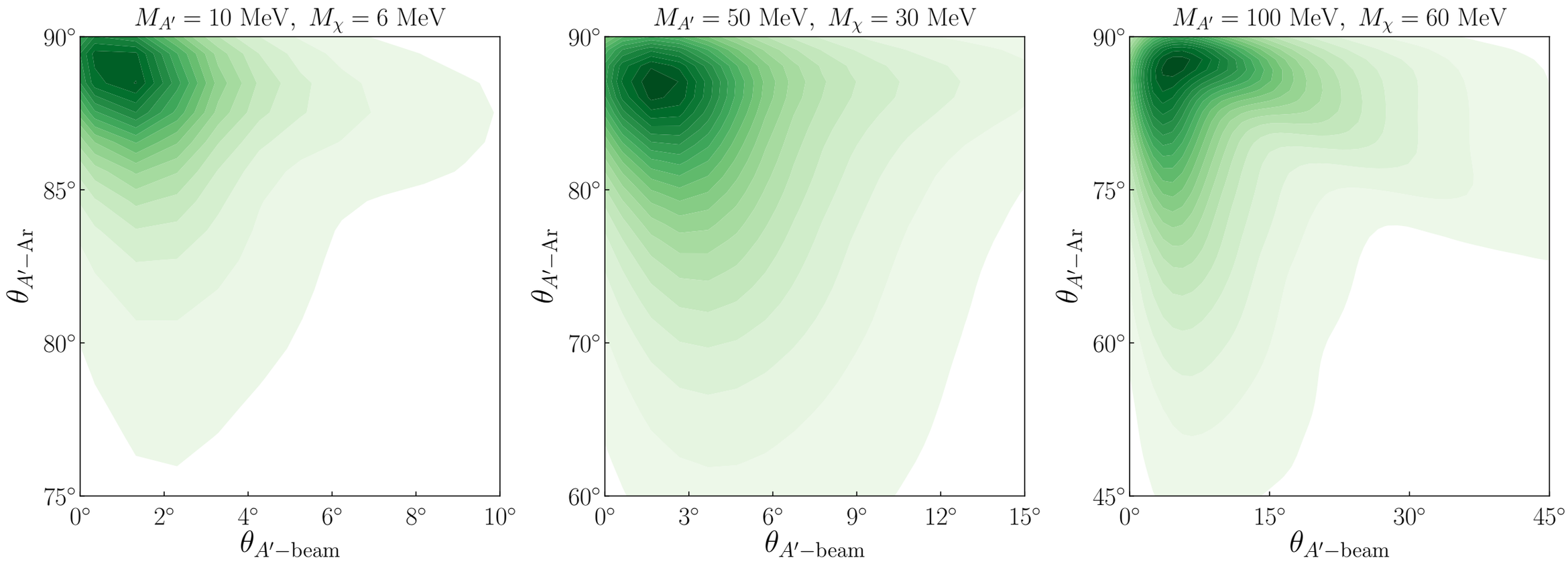

This is a generic feature that applies to all mass ranges we explore.

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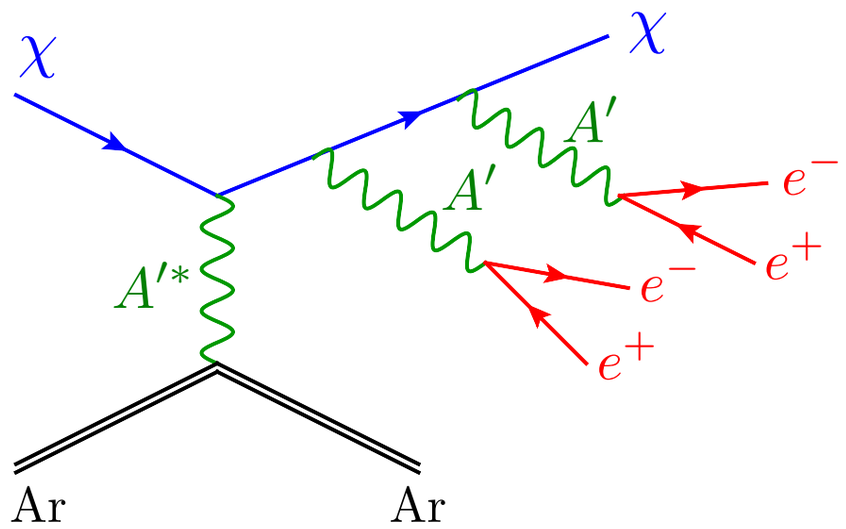
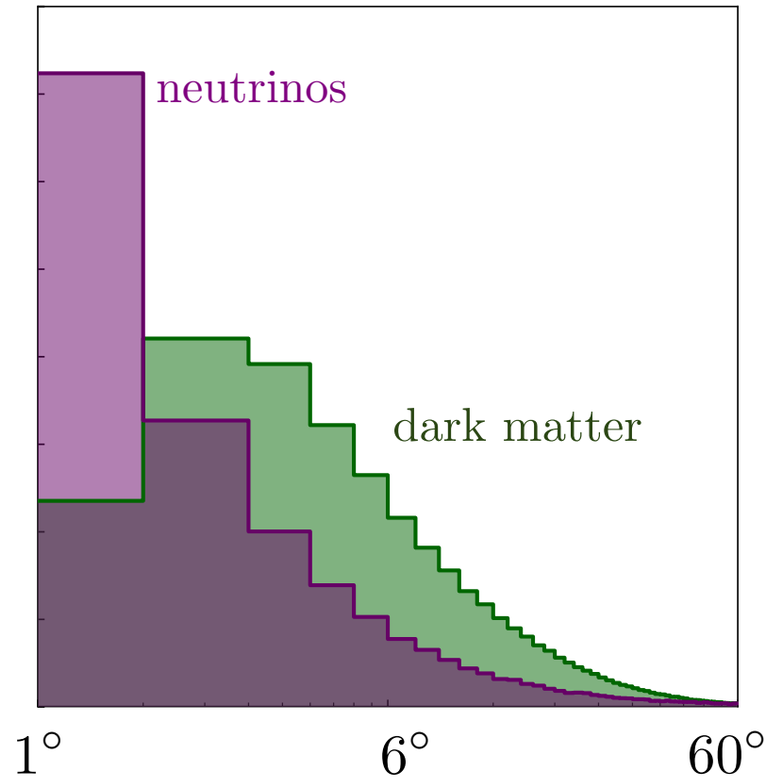
Future Directions

Beyond trident: multiple dark photon radiations important for large $\alpha_D \sim O(1)$.



DUNE PRISM.



- Large decay angles: observe multiple charged-lepton pairs.
- Collimated lepton-jets: unlike LHC, created inside the detector, exotic tracks from *dE/dx* measurement.

Conclusion and Outlook

Well motivated and exciting opportunity for ν experiments (e.g. DUNE) to probe the nature of dark matter.

Unlike neutrinos, plenty of new dark matter signals are allowed and to be tested, beyond elastic scattering — be open minded.

I discussed the dark trident signal: charged-lepton pair creation triggered by dark matter in ν detectors. Low background.

More broadly speaking, a wide variety signatures: *N,e* recoils, *Z'* resonances, lepton jets, MET … (c.f. new physics list @ LHC)

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thanks!